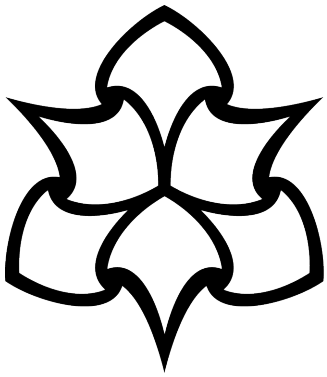

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REVIEW

International collaboration between collections-based institutes for halting biodiversity loss and unlocking the useful properties of plants and fungi

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Societal Impact Statement

The United Nations' Sustainable Development Goal (SDG) 17 calls for "strong global partnerships and cooperation" to support the other SDGs. The collections-based science community offers many examples of conservation of plant and fungal biodiversity, sharing, repatriation and aggregation of data, access to new technologies, supply of plant and fungal material, strengthening capacity of practitioners, and benefit sharing with the providers of biodiversity and genetic resources. Collaboration framed by workable multilateral treaties will increase our understanding of plant and fungal diversity, help halt biodiversity loss, and accelerate our sustainable use of plants and fungi and the exploration of their useful traits.

Summary

Collections-based institutes are at the forefront of generating knowledge and understanding of plant and fungal biodiversity. Through the analysis of occurrence data, the use of modern technologies to better understand the evolutionary relationships between species and documentation of their useful properties, the work of

collections-based institutes provides good models for conservation; addressing species loss and improving sustainable use of plants and fungi. Nevertheless, the pressure on the planet's plant and fungal diversity is relentless. We argue that a massive increase in the accessibility of preserved and living collections of plants and fungi is required. An increased scale of responsible exploration to both conserve and unlock the useful properties of plants and fungi is needed to deliver solutions to the many global challenges facing humanity and the planet. This article explores the role of collaborations between collections-based institutes and their partners in preventing biodiversity loss and delivering sustainable development. Drawing on examples from herbaria, agricultural and wild species genebanks, mycological collections, an international NGO, and the botanic garden community, we demonstrate how collaboration improves efficiency and impact. Collaborations can be peer to peer, institutional, governmental, national, or international, they may involve work with local communities and are frequently a combination of these. We suggest the five key benefits to collaboration and show that with trust, understanding, and mutual respect, powerful and sustainable partnerships develop. Such trust and respect are hard won, but once established, sustain a high level of commitment, enable development of shared long-term visions of success, and attract diverse funding streams.

KEYWORDS

botanic gardens, fungarium, genebanks, herbarium, metacollection, pre-breeding, seed banks, training

1 | INTRODUCTION

There is an imperative to develop and strengthen effective national and international collaboration between collections-based institutes as a prerequisite for improving our understanding of the diversity, distribution, interactions, and threats to plants and fungi, to halt their loss and to accelerate responsible investigation of their useful properties. Globally, these institutes house tens of millions of samples of plant and fungal biodiversity, with broad phylogenetic and geographical coverage. Significant progress has been made in aggregating globally dispersed occurrence data sets of both plants and fungi, most notably the Global Biodiversity Information Facility (GBIF Secretariat, 2019). This aggregation provides the bedrock for our exploration and understanding of plant and fungal diversity (Antonelli, Smith, & Simmonds, 2019; Bakker et al., 2020; James et al., 2018) and is a vital data resource to ensure conservation interventions are keeping pace with the increasing rate of species loss (Nic Lughadha et al., 2020). New global conservation targets have been proposed based on keeping the number of recorded extinctions of described species to less than 20 per year (Rounsevell et al., 2020). If this approach were to be adopted, the case to fund rapid acceleration in the digitization and aggregation of the globally dispersed occurrence data sets would become overwhelming. The density of sampling is significantly greater for plants than for fungi, with collections encompassing both living (plants, seeds, cultures) and preserved (herbarium and fungarium specimen, DNA samples etc.) material. While many large collections of plant germplasm are held in the Global South, including the Consultative Group for International Agricultural Research (CGIAR) genebank collections in South America, Africa, and Asia, most of the world's larger collections of preserved specimens are housed in the Global North, and predominantly reflect historical political alignments of European and North American collectors. The past 50 years have seen a rapid increase in national collections made by a growing cadre of local botanists and mycologists (e.g., Funk, 2015; Thiers, 2020).

Plant and fungal collections have enabled significant advances in visualizing national, regional, and global plant and fungal diversity, assessing threat levels, prioritizing future collection and research priorities, and supporting the establishment of in situ protected areas (Green, Weech, Drinkwater, & Wajer, 2019; Griffiths et al., 2015; Liu, Breman, Cossu, & Kennedy, 2018; Marshall, Wieringa, & Hawthorne, 2016; Meyer, Kreft, Guralnick, & Jetz, 2015; Meyer, Weigelt, & Kreft, 2016; Sosef et al., 2017).

Rapidly improving DNA extraction technologies for preserved material (Dodsworth et al., 2019; Hart, Forrest, Nicholls, & Kidner, 2016) have significantly increased the unravelling and publication of plant and fungal phylogenies (Naranjo-Ortiz & Gabaldón, 2019; Wortley, Bennett, & Scotland, 2002). These in turn have enabled more efficient identification of potential sources of useful plant and fungal traits to support agriculture, forestry, and medicine (Grace et al., 2015). Complementing this, the growth of ex situ collections of living plants in genebanks and botanical gardens provides a significant resource to accelerate breeding programs and improve

conservation outcomes for many of our most useful and endangered plant species (Donaldson, 2009). However, to unlock the true potential of these living ex situ plant collections, the phenotypic and genotypic characterization and evaluation of these materials needs to be accelerated (Cires et al., 2013; Tanksley & McCouch, 1997; Wood et al., 2020). This aggregation and genetic profiling of living material is driving the developing concept of the *metacollection* (Griffith et al., 2019). Such living plant collections afford an excellent opportunity to investigate plant–animal interactions (Baretto & Freitas, 2007; Vasconcellos & Freitas, 2007), develop propagation protocols, and better understand the potential adaptability of plants to shifting climate regimes (Seal et al., 2017). Living fungal and microbial material is also now more readily available where excellent progress in aggregating collection information and sharing accession data has been made (Ryan, McCluskey, Verkleij, Robert, & Smith, 2019).

Strengthening and rebuilding the inextricable link between people and the plants and fungi in their domain remains central for our increased understanding of the value of plant and fungal diversity to the custodians of extant natural habitats (Knapp, 2019). The Millennium Ecosystem Assessment (MEA, 2005) recognized that scientific findings and data need to be made available to all of society and that "a major obstacle to knowing (and therefore valuing), preserving, sustainably using, and sharing benefits equitably from the biodiversity of a region is the human and institutional capacity to research a country's biota." To effect change in the perceived value of biodiversity, it is not enough to simply document and describe. Local communities need to form part of collaborative arrangements and witness an improvement of their livelihoods resulting from the responsible and sustainable use of their biodiversity (Griffiths et al., 2019) and its longer-term care and repair (Reyes-García et al., 2018).

Sharing access to and information about biological collections is central to ensuring their value as a global resource for public good. Policy frameworks are required that accelerate the exploration and sustainable use of the wealth of properties and traits which remain locked in ex situ collections and natural habitats, while ensuring benefits of this access accrue fairly to the guardians and custodians of the plant and fungal diversity from where the materials originated (Williams et al., 2020).

The following eight case studies have been chosen to demonstrate the value of strong national and international collaborations in bringing together the strengths of biologists, biological collections, new tools and technologies, and local communities. They exemplify how such collaborative efforts are required if we are to rapidly identify plant and fungal-based solutions to environmental challenges and to halt biodiversity loss. Each also demonstrates various key benefits of importance to collaboration in any sector. These key benefits include synergy, greater efficiency, sharing resources, greater impact and leverage, and transfer of knowledge and technology.

Two examples illustrate how the aggregation of herbarium collections provides "big data" sets, strengthening national capacity—the Reflora program in Brazil and the Flora of Thailand. In Guinea, we explore how scientists working in tandem with government policy makers have secured lasting policy decisions for species, habitat, and site protection. Ensuring the role of local communities, the custodians of much of the planet's plant and fungal diversity, is presented in a study of fungal diversity in São Tomé & Príncipe. Our example from Costa Rica highlights the importance of parataxonomists in tackling large-scale identification of fungi. Making seed material more readily available to support agriculture is explored through case studies on the Adapting Agriculture to Climate Change project and Genesys. Finally, the pressing need to characterize our living plant collections is explained through the concept of the metacollection.

The benefits, commonalities, and lessons learned from the case studies are analyzed and we identify priorities for future collaborations to accelerate the exploration of plant and fungal properties and to go some way to halt the loss of biodiversity. Bringing complementary teams together is, of course, not a new approach; this article aims to ensure that the scientific and conservation communities consider how the hard work needed to foster strong collaborative networks ultimately delivers efficiency and impact.

2 | CASE STUDIES

2.1 | Case study 1—The Reflora Program

The Reflora program (Nic Lughadha et al., 2016) was established by the Brazilian government in 2010/11 with the specific aim to "retrieve and make available images and information concerning Brazilian plants deposited chiefly in overseas herbaria," and the broader purpose "to increase knowledge and conservation of the Brazilian flora" (Canteiro et al., 2019). Two primary lines of action were envisaged:

- digitization of Brazilian herbarium specimens deposited in overseas collections followed by virtual repatriation to create the Reflora Virtual Herbarium (RVH) hosted by the Rio de Janeiro Botanical Garden (JBRJ).
- a human capital mobility program designed to support research by individuals or networks involving Brazilian and non-Brazilian researchers.

Today, RVH includes 3.7 million digital specimen images sourced from some 86 herbaria. Referring to their standard Index Herbariorum code (Thiers, 2020) these collections are from seven European herbaria (B, E, K, P, PC, S, and W), seven United States herbaria (A, AMES, FH, GH, MO, NY, and US) and, since 2014 72 Brazilian herbaria, to create the world's largest tropical virtual herbarium and the first to have conservation outcomes as a primary focus.

A recent review (Canteiro et al., 2019) demonstrates that RVH fulfils its original purpose, having increased access to conservation-relevant information (Figure 1) for Brazil and for Latin America more broadly: half of the scientific publications citing Reflora and 81% of online survey respondents mentioned conservation-relevant outputs.

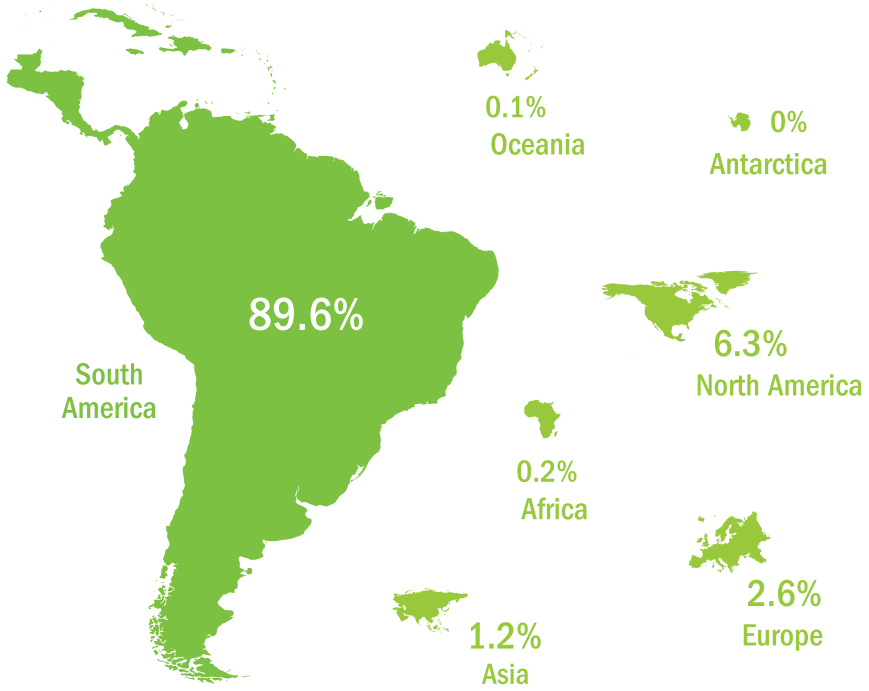

FIGURE 1 Visual representation of the global distribution of users accessing Reflora resources over the period May 2019 to early June 2020. Not to scale. The overwhelming majority of users are based in South America, but Reflora resources are also used on all other continents, except Antarctica

Conservation applications range from rediscovery of a rheophyte not seen for c. 170 years, which provided evidence to inform boundaries of an ecological corridor (Bove & Philbrick, 2014), to development of species checklists to inform management and monitoring in long-established Protected Areas that lacked such resources for many decades (e.g., Forzza & Lanna, 2020; Moreira et al., 2020).

Plant use by the corporate sector has been facilitated by access to authoritative data on which species are native to Brazil—vital for risk management in sourcing biodiversity inputs (Natura Cosméticos S. A., 2016) and in identification of species occurring naturally on metal-rich substrates which may have potential for revegetation following mining (Digital Plants, 2020). At the local scale, Reflora resources have been used in research documenting medicinal plant use by women resident in a settlement of descendants of freed slaves (Oliveira, 2015). Traditionally transmitted orally, this knowledge was considered at risk due to migration and lack of interest from young people.

Brazil's National Council for Science and Technology invited the Royal Botanic Gardens, Kew (RBG Kew) and the Muséum National d'Histoire Naturelle (MNHN) in Paris as their first international partners in developing Reflora based on: (a) the relevance of their collections for Brazil; (b) the strength of their existing relationships in Brazil, especially with the leading Brazilian institute in the program, the Rio de Janeiro Botanical Garden (JBRJ); and (c) the shared experience of these three institutes in delivering similar collaborative digitization projects (e.g., Latin American Plants Initiative, contributing to JSTOR Global Plants; Smith & Figueiredo, 2014). Stability and longevity of the resulting resources were key considerations in the decision that JBRJ, a publicly funded institute, should host the RVH. Effective use of resources was the primary driver in agreeing roles: specimens were imaged at MNHN and RBG Kew followed by data transcription from digital images transferred to JBRJ for inclusion in the RVH.

Reflora quickly expanded its original remit to include the List of Brazilian Flora (LBF), on an online platform developed by the publicly funded Federal University of Rio de Janeiro. Connecting these Reflora resources delivered synergies: the LBF provides a "dictionary" of names for the RVH while the linked images support the species distributions presented in the LBF. This resource has been enhanced to become the platform on which c. 900 botanists, collectively termed the Brazil Flora Group (BFG), are collaborating to complete, by 2020, the first Flora of Brazil online (BFG, 2015, 2018; Forzza et al., 2010; http://floradobrasil.jbrj.gov.br/). This first comprehensive account of the distribution, traits and habitats of Brazil's plants and fungi, contributes to all of the targets in the Convention on Biological Diversity (CBD) Global Strategy for Plant Conservation (Convention on Biological Diversity, 2012), enabling science-based conservation and sustainable use of Brazil's unrivalled natural resources. The BFG involves both a greater number and proportion of Brazilian collaborators than did the LBF, reflecting the growth and maturation of Brazilian capacity over the past decade.

2.2 | Case study 2—Developing the flora of Thailand

Floras are fundamental tools for scientists protecting global biodiversity. Ultimately, until we understand which plants occur where and why, we cannot take action to understand their threat status, protect them, or utilize their properties for sustainable development. The Flora of Thailand Project (http://www.dnp.go.th/botany/) aims to identify and describe every plant species in Thailand, enabling each species to be placed within future conservation programs, such as the Millennium Seed Bank Partnership (MSBP) project managed through RBG Kew to help develop the Thai vision for a National Seed Bank. The Flora of Thailand Project is a prime

example of a long term, multinational collaborative Flora project launched with clear timelines and goals to provide improved access to global collections of Thai plants, and offer essential baseline data to launch associated activities such as establishment of forest reserves and development of an active seed banking and conservation community.

The Flora was coordinated by the Bangkok Forest Herbarium, a key service provider for the Department of National Parks, Wildlife and Plant Conservation. With a particularly high involvement of local Thai botanists and authors (Figure 2), it is supported by a multinational editorial team from nine countries.

Other botanists from many countries continue to provide their specialist knowledge to write up accounts for families, genera, and species occurring in Thailand. The completion of the Flora of Thailand covering some 11,000 plant species, and the publication itself will represent the first of its kind in SE Asia, a region where no other modern-day Flora has, or is likely soon to be published, with the exception of the Flora of Singapore with its native flora of c. 2,700 species (Middleton et al., 2019).

The Flora was only possible through long standing international collaboration between European institutions, with their extensive historic collections, and a rapidly developing team of local Thai botanists. This collaborative effort and successful publishing timetable have not only fostered strong linkages with, and earned the respect of, key government departments, but also developed active plant taxonomic university groups with professors, postgraduate, and undergraduate programs in plant sciences. Fundamental to the project is increased access to collections, as well as fieldwork throughout Thailand to gap-fill taxa and regions. The Flora has benefited immensely from funding opportunities to bring Thai botanists to European institutions, especially a generous donation from the Carlsberg Foundation which recognized the benefits of the successful collaboration to date and was willing to fund the project toward its completion. In Thailand, receptive and organized in-country teams facilitated fieldwork for international visitors, and digitization of herbarium material from largely European herbaria made available on accessible online platforms is another extremely important factor in the project's success.

FIGURE 2 Undertaking fieldwork for the Flora of Thailand, botanists from the Bangkok Forest Herbarium, Mahidol University, Harvard Herbaria and RBG, Kew collecting in Phu Hin Rong Kla National Park, Thailand, Nov. 2018. Photograph: Dr. Tim Utteridge, RBG Kew

2.3 | Case study 3—Identifying the important plant areas of Guinea

Knowledge of plant diversity and distribution is essential for prioritizing in situ conservation. Guinea was until recently a country with little botanical capacity, with historical botanical collections deposited overseas (Paris, France and Dakar, Senegal), in effect remaining largely unavailable to botanists and decision makers in Guinea.

The University of Gamal Abdel Nasser, Guinea (UGAN), working with RBG Kew, recognized that to safeguard the Guinean flora from threats such as increased mining activities and to inform the creation of new protected areas for plants in Guinea, establishing a national herbarium was vital (now registered as HNG, Herbier National de Guinée), together with a long-term program of botanical exploration. The Guinean Ministry of Higher Education and Scientific Research, under which HNG operates, authorized the creation of a University Masters course in Biodiversity and Sustainable Development (http://www.herbierguinee.org/masters.html). International collaborators from RBG Kew and Ghent University, Belgium play a vital teaching role on this national training program. UGAN students, HNG and Ministry staff at all levels, and NGO representatives have been trained in plant identification, conservation management, International Union for Conservation of Nature (IUCN) Red Listing, and seed conservation. In addition, PhD programs on socioeconomic species including Bansouma (*Neocarya macrophylla* [Sabine] Prance), yams, and edible fungi, are being co-supported by the Guinean government and external funders.

The shared vision between local botanists, international partners, and Ministry staff secured UK Government Darwin Initiative support for the identification of a series of tropical important plant areas (TIPAs; Couch et al., 2019) and GBIF's Biodiversity Information for Development scheme funding for digitizing of herbarium specimens held at overseas herbaria. Transcription of data from specimen images completed at HNG by local students and botanists further strengthened the responsibility and role of the national facility in botanical exploration and understanding. A national plants database of some 19,000 occurrence records

provides baseline data for IUCN Red List assessments which fed into the TIPA process and which will also inform the basis of a national plants Red Data Book.

A National Working Group on TIPAs and Species Conservation Action Plans has provided the first opportunity for the many academics, government staff, and NGOs working on plant conservation in Guinea to work together in a formally framed consortium (Couch et al., 2019). This close and transparent collaboration led to the government accepting the 22 TIPAs (Figure 3), identified during the project and committing to put them into legislation as part of the Protected Areas network (Couch et al., 2019).

As a result of these successes, additional funding streams have opened for on-the-ground plant conservation (e.g., a Mohamed bin Zayed Species Conservation Fund grant to conserve Guinea's Critically Endangered National Flower *Vernonia djalonensis*), and the partners are continuing to strengthen and expand the collaboration.

2.4 | Case study 4—Fungal conservation in a global biodiversity hotspot

The islands of São Tomé and Príncipe are recognized as a global biodiversity hotspot (Mittermeier et al., 2004) with 107 of the island's 1,104 flowering plant species endemic to the islands (Fig ueiredo, Paiva, Stévart, Oliveira, & Smith, 2011). In contrast, knowledge of fungal diversity is much more limited with most lists still relying on the historical fungal collections and descriptions developed during the first half of the 1800s. Many specimens still await further study in European collections. Over the last 15 years, new records of macro-fungi have been made primarily by scientists involved in expeditions to São Tomé & Príncipe from the California Academy of Sciences, USA. Many findings continue to be reported (Cooper, Desjardin, & Perry, 2019; Desjardin & Perry, 2015a, 2015b, 2016, 2017, 2018) and species new to science were described such as the stinkhorn mushroom, *Phallus drewesii* (Desjardin & Perry, 2009).

While these recent collection efforts have advanced our understanding of fungal diversity on the islands, they have not involved local stakeholders, nor contributed to mainstreaming conservation efforts. In 2019, a collaboration between the University of Coimbra, Portugal, and the islands' government through the Directorate General of Forests (DGF) was designed and funded to fill this gap (Madureira, 2018). The project moves beyond the confines of documenting fungal diversity. Using agroforestry systems in forest buffer zones of the Obô Natural Park on São Tomé, the collaboration will increase the perceived value of fungal diversity for the livelihoods of local communities from the island by piloting mushroom production units and developing markets for edible and medicinal mushrooms. The project also includes training local farmers in the green economy and entrepreneurship, securing the conservation of fungal diversity through increased societal value.

Unlike in neighboring countries, the use of wild fungi for food and medicine is not embedded in the island's tradition. Only *Volvariella* sp. ("Útu" in the local dialect), collected by a few elders, and another edible mushroom, *Pleurotus tuber-regium*, well known and used across continental Africa, are used locally. However, during field work, several other known edible, or medicinal species with potential for domestication (e.g., *Auricularia* sp., *Ganoderma* sp.) were identified.

With a growing population and high levels of poverty (CEPF, 2015), forest resources in São Tomé are under increasing pressure. In the future, it is likely that small farmers will be forced to move to higher altitude forests where most endemic fungi have been found. The project delivered training in green economies and entrepreneurship, and through fungal domestication and providing an alternative source of income, the program will reduce the pressure of unsustainable exploitation of the remaining natural forest resource. The project delivered training in green economies and entrepreneurship, and through fungal domestication, provide an alternative source of income, the program will reduce the pressure of unsustainable exploitation of the remaining natural forest resource. The use of local isolates for production of domesticated lines will reinforce the value of local fungal diversity in the psyche of local communities leading to improved conservation outcomes. Projects such as this, which directly improve livelihoods, will go some way to reducing primary forest encroachment and the further loss of fungal diversity still largely unexplored.

2.5 | Case study 5—The Costa Rican National Fungal Inventory, integrating scientists, and parataxonomists

The Costa Rican National Fungal Inventory (1999–2005) remains one of the most ambitious fungal inventories to be undertaken in any tropical region. This large-scale international collaborative project was led in-country by the Instituto Nacional de Biodiversidad (INBio), a nationally mandated biodiversity research center. The project relied on the shared vision, commitment, and active participation of numerous in-country and international collaborators.

In addition to training three graduate students through the initiative, dedicated fungal parataxonomists were trained and employed, each a local resident of the Conservation Area they surveyed. These parataxonomists were stationed in the five targeted Conservation Areas spending 3 weeks per month documenting the fungal diversity and coordinating the input of local and visiting mycologists. A further week was spent identifying the material into broad fungal groups at the INBio fungarium. These extended field periods allowed parataxonomists to sample throughout the year (Figure 4), and throughout the country, something impossible for the Costa Rican and international team of scientists. Fruiting phenology and life history data were generated for a wide range of fungal species from varying forest types—novel data missing for most tropical regions.

Instituto Nacional de Biodiversidad facilitated visits by helping with in-country travel logistics, obtaining collecting and export permits, and supervising the development of Material Supply Agreements. In return, international collaborators along with Costa Rican mycologists managed the training of parataxonomists and graduate students both in the field and at the University of Costa

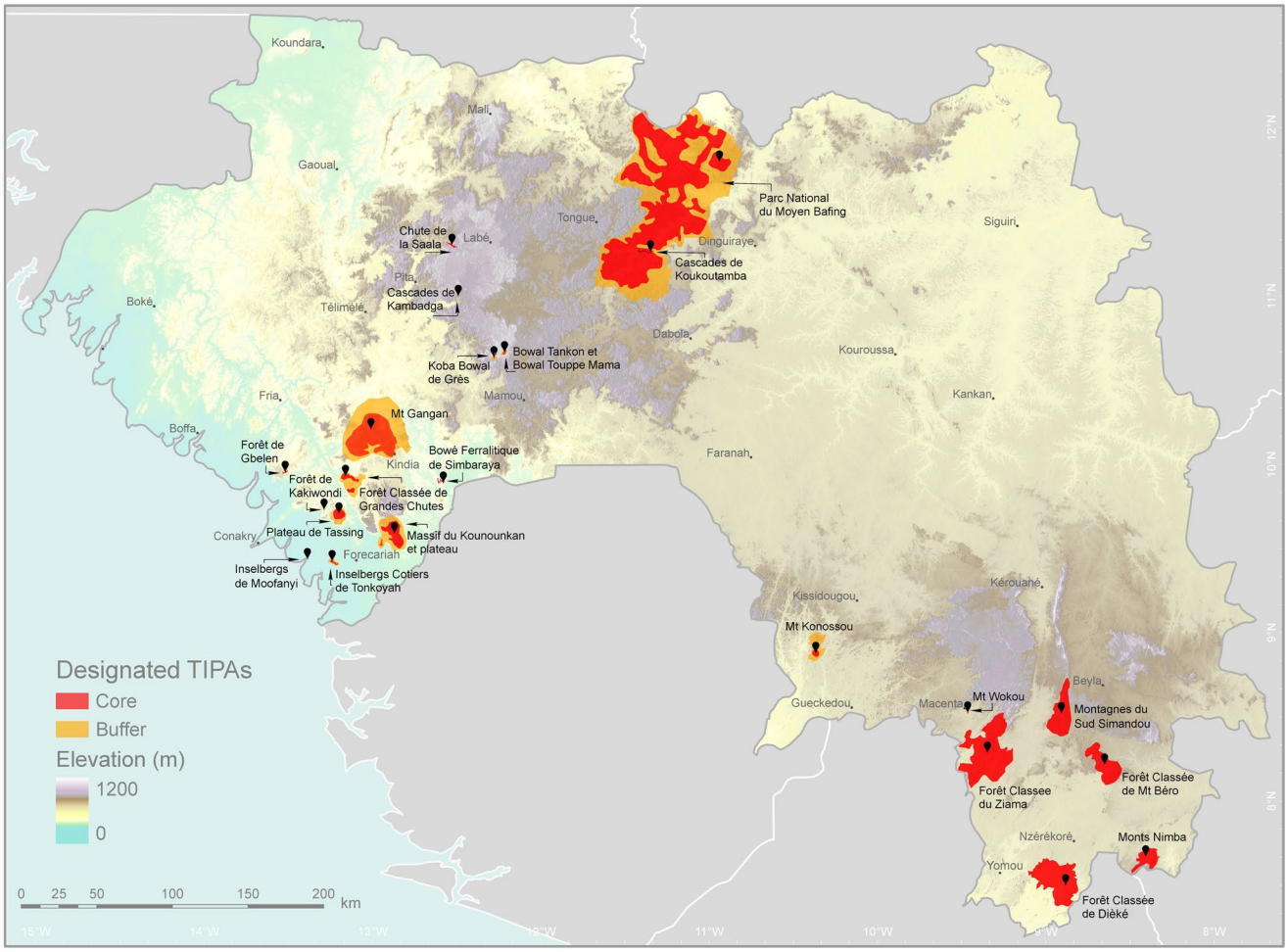

FIGURE 3 Collaborative research undertaken between national and international scientists in partnership with the national Government promises to significantly enhance Guinea's network of Protected Areas with the inclusion of 22 Tropical Important Plant Areas

Rica, building capacity of INBio's curators, identifying material in the herbaria of INBio and University of Costa Rica, and finally supporting the dissemination of the results.

While the project was successful in building a comprehensive collection and significantly adding to knowledge about the diversity, distribution, and phenology of Costa Rican fungi, it was not possible to fully meet its goal of completely documenting Costa Rican fungal diversity. Identifying collections demanded access to overseas fungal collections and the time of experts. While parataxonomists are extremely efficient at generating comprehensive collections from an area, they are only able to sort them into gross taxonomic groups. Additionally, due to internal structural issues, the fungal inventory program and INBio's bioprospecting initiatives did not develop a strong synergistic relationship, potentially limiting access to funding and impact. Inevitably, funding ran low after 6 years and INBio liquidated its assets in 2015. Many of the collections generated from the project were split, with material going to the Field Museum, Chicago, USA and the New York Botanical Garden, USA where they have been curated and digitized. The nearly 50,000 collections generated from this work are now part of the Costa Rican National History Museum, and information on them can be accessed through https://biodiversidad.museocostarica.go.cr/. For collections-based biodiversity institutes and partners it is not enough to make collections, their long-term management, access and use must be planned for. Funding for large initiatives always comes to an end and developing solutions after the fact is challenging and may not result in the best outcome. Nevertheless, the project has built a lasting international collaboration for the Costa Rican fungal community built on strong in-country leadership and the mutual respect of the international collaborators.

2.6 | Case study 6—Adapting agriculture to climate change: Collecting, protecting, and preparing crop wild relatives

The need to systematically conserve the genetic diversity of crops, including their wild relatives, through the establishment of ex situ collections of seed has been recognized by major international agreements. Articles 9 and 15 of the CBD (Convention on Biological Diversity, 2020), Article 8 of the associated Nagoya Protocol (Convention on Biological Diversity, 2011), and Articles 5 and 6 of the International Treaty for Plant Genetic Resources for Food and

FIGURE 4 During the Costa Rican National Fungal Inventory, fungal parataxonomist, Isaac Lopez, recorded and collected the iconic *Macrocybe titans*. Photograph: Dr. Gregory M. Mueller, Chicago Botanic Garden

Agriculture ("ITPGRFA" or "the Plant Treaty"; FAO, 2020a) all refer to the need to establish such collections and make suitable material available for the global good. The UN Sustainable Development Goal (SDG) 2 "Zero Hunger" also has a specific Target 2.5 which recognizes the importance of maintaining ex situ collections of domesticated crops and their wild relatives, promoting access to material and the fair and equitable sharing of the benefits of this use (UN-SDG, 2020).

A global gap analysis (Castañeda-Álvarez et al., 2016) made it clear that many crop wild relatives (CWR) were severely under-represented in genebanks, and as such not enough of their diversity is readily available for use. Like other wild plants, many CWR are rapidly disappearing from their natural habitats (Maxted & Kell, 2009). The implication of this erosion is far-reaching. Wild relatives of crop species hold many properties and traits that will be vital to unlock through breeding programs to develop crop varieties which are more resistant to biotic and abiotic stresses, more nutritious, and higher-yielding.

To address this challenge, the Global Crop Diversity Trust (Crop Trust) collaborated with RBG Kew's Millennium Seed Bank (MSB) and 25 national partners (Figure 5), on a recently concluded six-year program to collect and conserve the wild relatives of 28 globally important crops. This is part of a 10-year project, funded by the Government of Norway, aimed at providing plant breeders with the raw materials needed to adapt agriculture to climate change (https://www.cwrdiversity.org/).

Preparations for this major germplasm collecting initiative started in 2011, when a team of scientists from the Crop Trust, MSB, the International Centre for Tropical Agriculture (CIAT) and the University of Birmingham, United Kingdom, collaborated in a research program to identify high priority crop wild relative species and the geographic areas where they could be expected to be found. Data were gathered from more than 80 providers, including genebanks, herbaria, individual researchers, and online databases. This research resulted in three major outputs, available on the project website:

1. The Harlan and de Wet Crop Wild Relative Inventory, an annotated list of the CWR species in 108 genera.
2. A curated occurrence data set, representing the most comprehensive resource on the spatial occurrence of crop wild relatives.
3. Conservation gap analyses for 81 genepools including 28 targeted for collection by the project.

The results are summarized by Castañeda-Álvarez et al. (2016). Having identified the priority species and countries for collecting, national genebanks and others in 25 countries on four continents were engaged in a systematic, global collecting effort. This lasted from 2013 to 2019 and resulted in the collection of 4,644 unique seed samples of 371 different species and subspecies secured in national genebanks. Of these, 3,555 seed samples from 240 target taxa have been safety duplicated in the MSB. Passport data are now available on a dedicated page on Genesys (see case study 7 [CS7] below) for 3,488 accessions. In addition, 2,370 unique seed samples of 178 species have been distributed by MSB to nine international genebanks for multiplication, further characterization, and research. Collecting was conducted in accordance with relevant national laws and regulations. All collected material is made available with the Standard Material Transfer Agreement (SMTA) of the Plant Treaty.

Excluding management costs of the Crop Trust and the MSB, some USD6.6 million was spent directly on collecting grants to 25 partners. The cost of collecting one accession and thereby making this material available through the multilateral system is estimated at USD1400. It is worth noting that a few partners included regeneration activities in their budgets. In addition to the in-country regeneration activities paid for under the collecting grants, the Crop Trust has also set up agreements with the International Centre for Agricultural Research in Dry Areas (ICARDA) and the International Potato Centre (CIP) totaling about USD340,000 to regenerate the wild relatives of their mandate crops; wheat, barley, lentils, peas, forage, and other range species for ICARDA and potato for CIP. Pre-breeding is also a major component of the project, with work underway for 19 crops with more than 100 national and international partners in 48 countries. The pre-breeding projects are already making use of some of the material collected, in addition to material previously held in genebanks in support of climate change adaptation efforts.

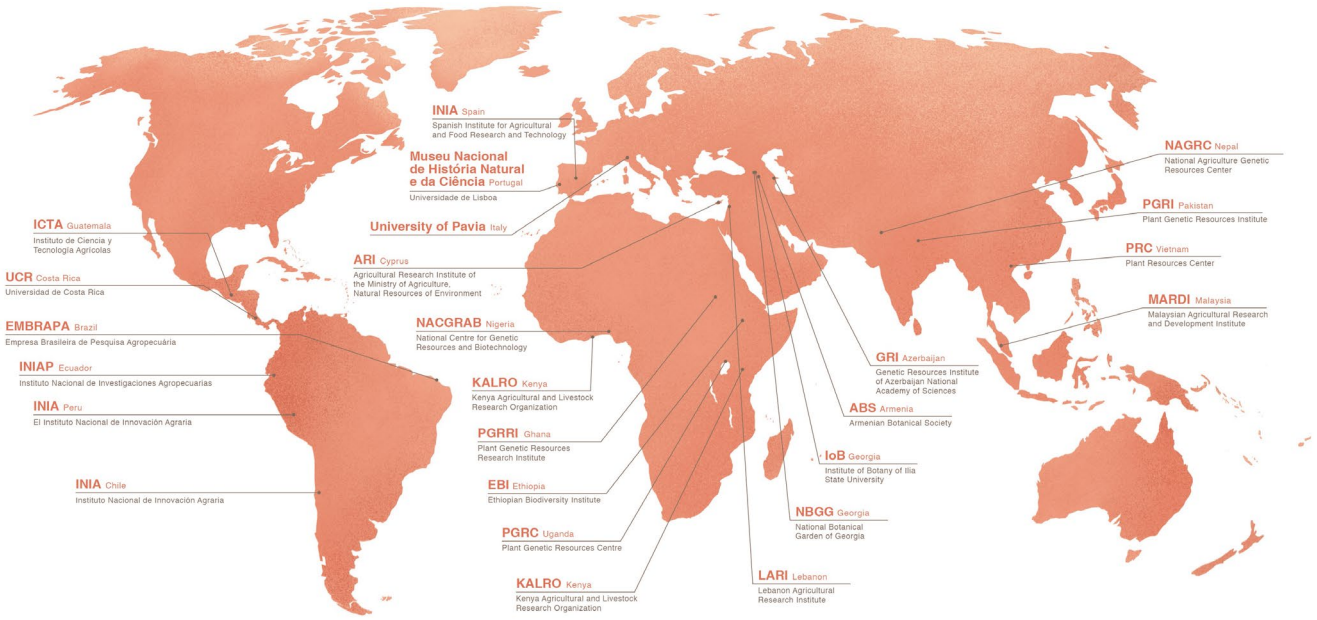

FIGURE 5 The 6-year collection phase of the Adapting Agriculture to Climate Change project saw 25 national collection partners lead on securing 4,644 seed samples from 371 wild relatives of 28 globally important crops

One example is the alfalfa pre-breeding project led by the South Australian Research and Development Institute (SARDI). The University of Pavia in Italy was one of the nine national partners that collected 20 species of wild alfalfa under the project's collecting program. The wild alfalfa seed samples sent to the MSB in 2013 were then shared with SARDI using the SMTA. These samples, together with seeds of alfalfa wild relatives sourced from other genebanks, were used to develop new breeding lines which were then evaluated for drought tolerance in Australia, Chile, China, and Kazakhstan. Some of these have shown outstanding performance (Humphries et al., 2018).

Through this project, a wealth of new material has been collected and further developed that is now being introduced into breeding programs and will continue to be available to breeders for years to come under the terms and conditions of the SMTA. However, policy positions among relevant national ministries are still divergent and in flux in some cases, jeopardizing such conservation efforts. Future initiatives need to place more emphasis on making CWRs more widely recognized as global assets with appropriate mechanisms in place for their conservation and explore opportunities to influence decision makers at different levels.

2.7 | Case study 7—Agricultural genebanks and Genesys

In the years leading up to the development of the Plant Treaty there were three major online repositories of accession data for crop plants, crop wild relatives and other useful species, those of: (a) The United States Department of Agriculture-National Plant Germplasm System (USDA-NPGS) called the Genetic Resources Information Network (GRIN); (b) The European genebank networks European Search Catalogue for Plant Genetic Resources (EURISCO); and (c) the System-wide Information Network for Genetic Resources (SINGER) of the 11 international genebanks of CGIAR. These represented significant resources that had been available individually for some time but were not interoperable.

Article 17 of the Plant Treaty inter alia acknowledged the pressing need for a system for sharing genetic information among breeders, farmers, and researchers (FAO, 2020b). This Global Information System on Plant Genetic Resources for Food and Agriculture known as GLIS, builds on, integrates, and enhances existing information systems in this area. EURISCO, the FAO World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture database, genomic databases, and other systems are all elements of GLIS, and they serve the needs of specific audiences.

Genesys, a key component of this global system, focuses specifically on agricultural genebanks and makes information on their collections accessible to the world. Genesys attempts to address the need for interoperability in one of the most significant initiatives bringing the global agricultural genebank community together. Genesys is a stable mechanism, managed as a core function by the Crop Trust with secure, long-term funding from the CGIAR Fund. With an initial focus on the aggregation of the three largest data sets of plant accessions referred to above, the Genesys platform was first launched by the Crop Trust in 2008, aggregating 2 million accession records from SINGER, EURISCO, and USDA-NPGS. Today Genesys holds over 4 million accession records from 459 national agricultural genebanks from around the world. This is thought to represent approximately half of the total number of accessions held in ex situ collections globally. Most data providers regularly update information on their holdings on Genesys. Genesys serves three major user

groups: genebanks who wish to share their accession data, potential users of this material, and other researchers interested in both the status of conservation efforts and influencing national and global conservation policy.

Genesys is a database through which national, regional, and international genebanks make available passport, characterization and evaluation data, as well as images on accessions that they conserve. For national genebanks who might not have the capacity to develop and maintain their own online presence, an opportunity to publish information on their collections on Genesys is a means to ensure their collections are known to users across the global agricultural sector. Genebanks survive the uncertainties of national and international funding streams when they can demonstrate their key role in sharing material and knowledge for the benefit of agricultural development. Raising their global presence increases their audience, and potentially increases demand for their material. External funders and grant schemes frequently insist that data on resources secured through their investment are available online.

Rather than searching through numerous separate databases, Genesys enables users to simultaneously search hundreds of genebank collections with a single search term or filter. In this way, Genesys makes the essential preliminary stage of the work of the breeder and researcher more efficient. As an aggregated data set, Genesys facilitates the submission of germplasm requests to the original genebank, where requests are dealt with subject to legal and phytosanitary conditions and other national genebank distribution policies that may be in force.

Close collaboration between Crop Trust staff responsible for Genesys and genebank documentation staff allows for efficient sharing of methodologies and toolkits in both directions. Genesys facilitates the adoption of best practices on data management and publication by the genebank community as a whole. The functionality of the system continues to evolve to serve genebank managers and diverse users alike.

2.8 | Case study 8—Collaboration across Botanic Gardens, agricultural genebanks, and wild plant seed banks: Developing the metacollection

Worldwide, over 3,000 botanic gardens, agricultural genebanks, and wild plant seed banks maintain living collections of potentially up to one-third of all known plant species. Botanic Gardens Conservation International's (BGCI) PlantSearch database includes 1.47 million living collection records provided by 1,100 such institutions (BGCI, 2020).

The use of this living material for breeding, species recovery and habitat repair and restoration, coupled with the rapid exploration of plant and functional traits through improved genomics techniques is one of the key purposes of living plant, seed, and fungal ex situ collections. The collective conservation power of these institutes is, therefore, an essential resource to stop plant extinction and aid exploration of plant and fungal properties.

Clearly a single plant grown in one botanic garden will rarely embody sufficient genetic diversity to fulfil a conservation need and there are also cases where the collections of a target species across many gardens will include a large proportion of clonal copies or at the very least, such a narrow genetic base that it does not in fact provide a viable breeding capacity. Collaboration across sites will identify many opportunities where combining holdings of the same species across collections will significantly increase the genetic diversity and offer the source of material for assisted reproduction of threatened species (Wood et al., 2020).

Globally dispersed collections should be considered as parts of a whole, with the sum of those parts being of greater value than the individual collections. This concept of the metacollection has its roots in the zoological community (Bingaman Lackey, 2010) and is now gaining importance and interest within the botanical community. The metacollection represents:

> The combined holdings of a group of collections. For Botanic Gardens, metacollections are envisioned as common resources held by separate institutions but stewarded collaboratively for research and conservation purposes. Networking multiple collections into a single metacollection increases potential coverage within a group, allows broader access to greater diversity, dilutes risk of loss, and can reduce maintenance costs (Griffith et al., 2019).

Botanic Gardens Conservation International's PlantSearch database allows species in living, seed and tissue collections to be identified, allowing users to contact individual gardens or genebanks for access to material. The Plant Collections Network of the American Public Gardens Association is a good example of the aggregation of accessions data of U.S.-based living collections from public gardens and the germplasm held at the USDA-NPGS. These data are available online and can be searched (Plant Collections Network, 2020). Both are examples of useful resources but there remains no global solution to share accession-level data across ex situ collections of wild plants.

One of the aims of BGCI's Botanic Garden Accreditation Scheme (BGCI, 2020b) is to encourage botanic gardens to make information about their living plant collections more widely available and adopt recognized standards for data transfer such as Darwin Core (Wieczorek et al., 2012) and the International Transfer Format for Botanic Garden Records (ITF2, 2020). Adopting these standards is the first step to forming metacollections. The metacollection requires the adherence to internationally recognized standards of data and material availability. The Darwin Core standards have largely met this requirement for aggregation of biological observations. The documentation standards for agricultural genebanks (Alercia, Diulgheroff, & Mackay, 2015) are well documented and broadly adopted as Multi-crop Passport Descriptors.

Through its collaborative network, BGCI promotes metacollections to ensure the conservation of priority species—especially for

those species whose seeds cannot be dried and frozen in conventional seed banking techniques (Fant et al., 2016; Griffith et al., 2019). Formalizing these collaborations into Global Conservation Consortia (Global Trees Campaign, 2020) have brought together gardens that have significant collections of a particular plant group. To date, such metacollections of Quercus (Oaks), Magnolia, Acer, and Rhododendron, have amalgamated important data on the distribution of ex situ collections of each genus (e.g., Beckman et al., 2019). Such collaboration establishes an audit of the ex situ collections as the first step, with further analysis of the metacollection facilitating identification of taxonomic and provenance gaps, planning for future collection missions and safety duplication across collections, as well as enhanced opportunities for collaborative research and capacity building.

The MSBP's global seed collection (MSBP, 2020) has increased the availability of seed from some 40,000 plant taxa across 365 plant families (Liu et al., 2018). As the largest repository of seed from wild plants, the MSB uses an online portal to share collection data between partners (http://brahmsonline.kew.org/msbp). This represents the only place where data on the wild seed collections of conservation value held across this global partnership of seed banks is brought together. Collection strategies in support of forestry, horticulture, and agriculture have developed a strong focus on establishing multi-provenance ex situ collections from a relatively narrow range of species (Guarino, Ramanatha Rao, & Reid, 1995). However, with notable exceptions (Castañeda-Álvarez, 2016; Hoban, Kallow, & Trivedi, 2018; Trivedi & Kallow, 2017) little emphasis has thus far been placed on collection strategies that aim to capture a wide range of provenance genotypes of key wild species. The gap analysis undertaken for many ex situ collections of crop species needs to be adopted for conservation collections of priority wild plants to ensure this global collaboration develops metacollections that can play their part in halting biodiversity loss.

Developing the concept of the metacollection of living plants across the botanic gardens community and the seed collections held in global and national genebanks promotes a positive exchange of data and material between collections. Several methods for undertaking gap analyses at the population or provenance level have been developed and used to prioritize collection of the known landraces of *Phaseolus vulgaris* L. (Ramirez-Villegas et al., 2020), a sample of socioeconomically important South American trees (van Zonneveld et al., 2018) and more broadly for a large sample of c. 7,000 useful wild plants (Khoury et al., 2019).

For many years agricultural genebanks such as the USDA-NPGS have focused on multi-provenance collections of selected species of agricultural importance. This has not been the case for botanic gardens and conservation seed banks such as the MSB. While a wide range of species may be desirable for display purposes in gardens, for conservation collections, a more focused approach is needed. The aggregation of accession data for living ex situ collections needs to advance rapidly in order to identify gaps in provenance of collections. The underlying genetic characterization of different provenances will need to become a standard activity for the management of the individual accessions for priority species of conservation concern or those with the potential for sustainable use.

3 | SYNTHESIS

International collaboration across biodiversity projects offers numerous benefits. Through the eight case studies presented we have identified the five key benefits to collaboration: (a) synergy; (b) greater efficiency; (c) sharing resources; (d) greater impact and leverage; and (e) transfer of knowledge and technologies. We remain mindful that successful collaborations are environments where trust and professional respect within and between partners flourish. Here, we provide the evidence that collaborative models of working offer the best chance of short-term project success and longer-term impact.

3.1 | Key benefit 1: Synergy

Designing and developing collaborative teams that bring together complementary knowledge, skills, and expertise deliver more than its individual members could.

There is an urgent need to bring together the collections, expertise, and resources frequently dispersed across countries, national institutes, and individual research groups. The existence of this disjunct means that no country can work in isolation to describe and sustainably utilize its plant resources (Grieneisen, Zhan, Potter, & Zhang, 2014; Independent Group of Scientists appointed by the Secretary-General, 2019). Whether we look at flora documentation at the national level (case study 1 [CS1], case study 2 [CS2]), the exploration and sustainable use of fungal diversity (case study 4 [CS4], case study 5 [CS5]), the collecting and sharing of seed material and related information for agriculture (case study 6 [CS6], case study 7 [CS7]), or improving the value of our living collections in botanic gardens (case study 8 [CS8]), none of the positive outcomes would have been achievable by any one institution or country working in isolation.

Collaborations that share a common understanding of program aims and develop mutual respect for the value, contribution, and responsibilities of each partner are the most effective at project delivery and the uptake of research findings. CS1 demonstrates the advantage of building on existing long-term collaborations, while case study 3 [CS3] and CS6 brought new partners together, who had never had the opportunity to collaborate before. CS4 shows that the historic, often colonial, exploration and cataloguing of fungal diversity in São Tomé and Príncipe had little long-term impact in building ownership of that knowledge in country. Introducing local communities and island government as key collaborators, with a strong local leadership role, developed a new and powerful sense of custodianship of this fungal biodiversity. Building on the experience and know-how of the local

communities while supporting livelihoods through the sustainable use of this fungal diversity, enhanced the longer-term outlook for the conservation of the fungal diversity of São Tomé and Príncipe, which is now very positive.

Ensuring that all the relevant partners are involved in a collaboration from inception should include not only those needed to deliver the findings, but those who will implement these findings. This is clearly evidenced in CS3 where many academics, government staff, and NGOs involved in plant conservation in Guinea worked together in a formally framed consortium leading to all 22 suggested important plant areas being accepted by government. The inclusion of government representatives from the outset was key to ensuring the uptake of the research findings to bring about this significant improvement of national conservation policy.

CS6 brought together three major work packages over a 10-year program each requiring a different set of skills from different collaborators: (a) An initial gap analysis of existing CWR collections led by CIAT and the University of Birmingham; (b) the 6-year global seed collection program undertaken by the national genebanks and herbaria coordinated by the MSB including significant training and technology transfer; and (c) the data aggregation and seed supply systems through the Genesys team and the MSB seed supply mechanisms. As well as providing technical support, the Crop Trust provided the long-term program oversight and coordination and managed the Norwegian Agency for Development Cooperation project funding. Collectively this was a powerful team, delivering the short-term products of the separate work packages and ultimately, the longer-term impact of improving the availability of high-quality seed of numerous CWR plant species to pre-breeders. No one organization in this collaboration could have delivered these outcomes on their own.

A similar gathering of collaborators with complementary knowledge and skills is visible in all the case studies. For some it means the bringing together of those with differing areas of expertise (e.g., CS6), for others it involves the bringing together of those with varying levels of knowledge and access to improve these through shared experience (e.g., CS5 and CS8).

Through the process of examining existing living collections across botanic gardens, and other institutions, CS8 demonstrated complementary expertise within and across gardens. Adding value to these living collections and defining the metacollection demands the synergy of field, horticultural and lab-based skills.

3.2 | Key benefit 2: Efficiency

Complex conservation projects risk being cost-inefficient if undertaken by individual researchers or organizations; collaboration brings cost efficiencies, shared technologies, and access to local knowledge, land, and resources.

Case study 1 utilized the imaging technologies invested in by Kew and Paris herbaria to deliver the quantity and quality of image capture of herbarium specimens housed in their collections for repatriation, while transcription of label data was undertaken at JBRJ. This was innovative for its time, achieving cost efficiencies by minimizing the number of additional staff to be employed in Europe while creating opportunities for numerous Brazil-based students to undertake data capture on a part-time basis. This in turn increased students' familiarity with the attributes and uses of herbarium material, and with their national flora. A similar model was subsequently employed in CS3, where HNG botanists transcribed label data from images working with local students and botanists, strengthening the responsibility and role of the national facility in botanical exploration. Investment may be required to achieve longer-term efficiencies. In the early stages of CS3, RBG Kew recognized that a dedicated staff member to coordinate the collaboration would ultimately deliver greater efficiency. Alongside the specific roles and responsibilities of project partners, the coordination of this new collaboration in Guinea was crucial to its success.

The hard-won trust developed between organizations over long-term collaborations can also lead to efficiencies. The delivery of CS2 was built on trust developed since the 1960s. Because of this mutual respect between Thai and overseas researchers, access to research permits, obtaining prior informed consent to access land and the often-arduous logistics required to organize fieldwork have all become more efficient. Thai researchers similarly benefited from increased ease of access to partner institutes and their facilities. Similarly, CS5 benefited from efficiencies in logistics and for new collecting sites and fieldwork planning because of the intimate knowledge of target regions and connections with local people and institutions of in-country partners. CS5 massively accelerated the generation of new collections, together with distribution and ecological data. This would not have been achieved in the project time scale by any one or two of these sets of participants working alone.

CS6 provided an opportunity for national partner genebanks to establish a structure and process for collecting, conserving, and sharing CWRs. Most partners had never worked on CWRs and had to develop processes for obtaining permits, gaining clarity on the appropriate policy regimes (CBD vs. ITPGRFA) and regulatory requirements that apply to CWRs and issuing authorities, and determining the most effective and efficient way of working. The unit cost for a collection of USD1400 results from the granting of in-country funds to local genebank partners, rather than using overseas collection teams to undertake the collection program.

Genesys (CS7) provides its services in collaboration with national, regional, and international plant genetic resources databases and data services. It has therefore reduced the need for individual national agricultural genebanks to necessarily invest in the development and maintenance of high-quality data portals, while enabling those lacking resources to share their data. Project-based development of new databases often results in systems that do not have the means for maintenance and support past the project end-date.

The adoption of established standards for genebank data publication and participation in Genesys ensures that experiences and knowledge is shared and available to newcomers. In addition, this standardization of data from a wide variety of sources, with varying

formats and quality, makes its use much more straightforward, saving users significant time and effort involved in data cleansing.

For many researchers it is now far more efficient to search and identify sources and provenances of material that they require by using Genesys rather than searching the websites of individual genebanks. Users will still need to contact individual genebanks for material supply but can make time-saving decisions about which genebank to approach, for example, by using material that may already be in their country, thus, avoiding often lengthy import requirements.

Documenting metacollections of living plants in botanic gardens, agricultural genebanks, and wild plant seed banks (CS8) enables efficiencies in filling provenance gaps in collections, new collections can be carefully targeted and these organizations can modify what parts of their collections they invest in. This process not only makes the collections more valuable and useful for conservation, but also increases efficiencies for individual organizations to maintain their living collections.

3.3 | Key benefit 3: Sharing resources

The trust and mutual respect developed through collaborative working helps remove barriers to sharing and aggregating specimens, data, and material held in dispersed collections.

Case study 1 and CS3 increased access to hitherto dispersed herbarium collections of Brazilian and Guinean plants though digital repatriation of specimens. CS1 developed an aggregated virtual collection and supports a national plant list (http://reflora.jbrj.gov.br/), resulting in increased availability of robust data, delivered in a format that now offers scientific rigor, intrinsic value, and ease of use for many audiences. CS3 produced the Guinea plants database available locally to botanists and allied users of these data.

Case study 1 also exemplifies financial resource-sharing across nations: in its first phase the international components of the program were funded mainly from Brazil, through a combination of private sector and research foundation funds. Thereafter, funding sources were diversified within Brazil. New funding also resulted from open lines of communication between United Kingdom and Brazilian funders at the highest level, enabling UK Newton funds to support the continuation of UK digitization efforts and Brazilian researcher visits until 2016 (Grimes & McNulty, 2016; Nic Lughadha et al., 2016).

Voucher specimens of fungi made during CS4 are now, for the first time, deposited in the National Herbarium of São Tomé (STNH) with duplicates in the University of Coimbra Herbarium, Portugal (COI). Further benefit will arise when the planned digitization of fungal material at COI is completed.

Similarly, CS7 provides an established platform using consensually agreed data standards resulting in data that is compatible and simpler to utilize, enabling delivery of "big data" to a global audience. Many examples of data aggregation and sharing of information relating to biodiversity can be found in the literature and their resulting online databases, which have vastly improved access to occurrence data for plants and fungi.

Case study 6 strengthened mechanisms for using SMTAs, to transfer collected material, giving researchers the potential to more easily access quality seed material and data on multiple occasions without the need to renegotiate terms of the supply. The 2019 progress report to the Governing Body of the Plant Treaty (ITPGRFA, 2019) indicates that at least 2.2 million accessions of material are available through the Multilateral System of the Plant Treaty, representing a 35% increase in available material since 2017. CS6 also demonstrates that through the duplication of seed material to partner genebanks, security and health of the collections is assured. Where seed quantities allow, the duplication of seed material to a collaborating institute is a key management standard.

The collaborations that are bringing about the sharing of collections data across botanic gardens, agricultural genebanks, and wild plant seed banks as demonstrated in CS8 now mean the development of ex situ breeding populations of critical plant species is possible. A single botanic garden operating independently is unlikely to be able to deliver conservation outcomes for some critically endangered plant species, and this initiative of sharing and exploring accessions data is leading to improved protection of these species. The sharing of collections and their associated data necessarily entails the sharing of other resources between partners, such as expertise and technologies. In so doing the capacity of partners to manage and utilize their collections increases.

3.4 | Key benefit 4: Impact and leverage

Combining complementary skills (key benefit 1), efficiency (key benefit 2) and the trust, mutual respect, and confidence to share their resources (key benefit 3) our case studies show how collaboration can bring about long-term positive change, lead to mainstreaming of new behaviors, deliver more sustainable funding, and drive a cessation of biodiversity loss and an increase in its exploration. Successful collaboration thus has impact and leverage beyond the initial project deliverables.

Delivering key messages to the right audience in the right way greatly improves conservation outcomes. The multinational, multilingual nature of CS1 provided a diversity of voices and messaging, resulting in a high level of awareness of the Reflora resources among target audiences. Bringing together the extensive media coverage for Reflora in Brazil, along with the numerous scientific papers in national and international journals, leveraged further outputs not envisaged at the inception of the program: a UK Government-commissioned full-color bilingual booklet explaining the rationale and significance of Reflora, celebrating the success of the initiative (Nic Lughadha et al., 2016); and an in-depth review of the users of the Reflora resources (Canteiro et al., 2019). That the Reflora program continued even when Brazil's economy faltered is due largely to the creativity and determination of the JBRJ researchers who communicated the central relevance of the Reflora resources to other emerging initiatives, helping to leverage more funding to integrate and support

them (e.g., Sistema de Informação sobre a Biodiversidade Brasileira, Inventário Florestal Nacional; Forzza et al., 2017). Embedding key botanical resources into strategic government decision making agencies ensures a rapid flow of data between research teams and policy development, while mainstreaming activities into the core business of governments and institutions strengthens national conservation policy through evidence-based recommendations.

The benefit of including government partners in collaborative teams is well demonstrated in CS2, CS3, and CS4. The Thailand Department of Forestry is one of the key target audiences for increased knowledge on Thailand's plants and the Flora team is now a well-respected "home-grown" and "home-owned" facet of the forestry sector in the country, appropriately integrated into the development of national conservation policy. In Guinea, the program has enabled plant conservation to advance up the national agenda, challenging long-held perceptions and ultimately bringing about changes in national policy, adding a new level of protection to some of the country's most important plant areas. This would not have been possible had the close and transparent collaboration not included representatives from the relevant ministries at the outset. In CS4 the government of São Tomé & Príncipe, through the DGF, is a key partner, establishing community-led forest management areas, empowering communities, and securing their commitment to the success of the agroforestry scheme. The government's involvement in the project ensured that the agroforestry benefits were not simply dependent on the project's funding period and has enabled research results to inform national policy. For a different reason the interest in fungal diversity has been increased in Costa Rica as demonstrated in CS5 where an active website and field guides continue to raise the profile of fungal diversity not only in Costa Rica, but more widely in Central America.

Case study 6 showed that many national genebanks and their work on CWR gained a significantly higher national profile because of their collaboration with the project. Responding to a growing interest in CWR by local communities, the Pakistan genebank organized the first ever national workshop on CWRs. In Uganda, workshops were organized in rural communities to inform villagers about CWR as part of the country's requirements for collection. The strengthened global collaboration on CWR conservation, with greater engagement and links between funding institutions, national partners, and their government institutions, has increased interest in and opportunities for conservation of CWR, with important benefits for the future of agriculture. Interest in fungal diversity has increased in Costa Rica as demonstrated in CS5, in this case through an active website and field guides which continue to raise the profile of fungal diversity not only in Costa Rica, but also more widely in Central America. While CS4 raised awareness of the importance of previously neglected fungal diversity, engaging stakeholders in its management and sustainable use.

The global reach of Genesys in CS7 provides the opportunity for individual collaborators to demonstrate the value of their agriculturally important collections. This is a powerful way for smaller national genebanks to significantly enhance national and international awareness of their work on germplasm conservation, helping to leverage sustained funding and influence. Openly sharing data does not come naturally to most organizations. The very nature of data aggregation requires a high quality of data to be provided by the data donors. Genesys has provided guidance and assistance to genebanks in updating their data management practices and internal information systems, resulting in improved documentation of existing collections and the adoption of high-quality data management practices going forward. Collaborative data sharing, like that in CS8, can also lend authority and credibility to the shared data. Recommendations arising from this communal resource will have a higher profile and are more likely to be acted upon as they have the weight of multiple institutions behind them.

3.5 | Key benefit 5: Transfer of knowledge and technologies

Transfer of technologies and the resulting strengthening of capacity among collaborators increases the likelihood of activities being sustained at the point of need.

Training remains one of the most sought-after benefit-sharing measures to accrue from facilitated access to genetic resources and is often referred to as a typical nonmonetary benefit of access to genetic material (Biber-Klemm & Martinez, 2006; CETAF, 2019). Our case studies have described different types of knowledge and technology transfer, each supporting efficiency, developing longer-term impact, and leverage through alumni.

The mobility of partners throughout CS1 enabled an unprecedented number of Brazilian researchers to make study visits to European herbaria where they not only accessed the collections for their research, adding value to the many specimens for which they provided expert identifications, but also engaged in mutually beneficial interactions with scientists at these institutions, resulting in numerous coauthored publications.

The development of active university courses in Guinea (CS3) advancing the development of early career researchers, the establishment of taxonomic research groups in the Universities of Thailand (CS2), and the training of the future Curator of the STNH by the University of Coimbra (CS4) are examples of knowledge transfer that will have a lasting legacy for the future of botany, mycology, and conservation science in these countries. More broadly CS2 continues to instill a sense of pride and enthusiasm in young Thai botanists and connections with global botanists and taxonomists interested in their flora. While pride and enthusiasm are not often referred to in training or technology transfer outputs, this study illustrates that developing these qualities is a core part of the skill set required to deliver key national messages to halt biodiversity loss, raising the profile of plants and fungi in the national dialog.

Case study 4 worked in partnership with other projects to identify opportunities and constraints to improving the livelihoods of local communities and provided training in the green economy and entrepreneurship to local farmers. The training has empowered local

farmers and developed new local leadership to support the mainstreaming of agroforestry management models built on tradition, culture, and existing local and regional market needs.

The provision of job training and career skills to the parataxonomists and building a strong and respectful collaborative team among in-country scientists, international collaborators, and local collectors was key to success in CS5. Transfer of knowledge is not necessarily a one-way process. In addition to the flow of support to Costa Rican mycologists to enhance field collection and identification techniques, and improve collections management, there was an equally important flow of learning about Costa Rican ecology, fungi, and culture from Costa Rican mycologists, students and parataxonomists to other collaborators.

Significant technology transfer occurred throughout the CWR collecting phase of CS6 resulting in the enhanced capacity of many national partners. Some were paired with local CGIAR genebanks who provided technical support as well as the opportunity to gain relevant experiences from international partners, strengthening long-term links between partners and their regional CGIAR centers. The multicountry nature of CS6 allowed for regional training courses such as the Seed Conservation Techniques courses delivered by the MSB. Bringing regional partners together provided opportunities to develop potential new regional collaborations, facilitated cost-effective exchange visits, and helped develop relationships that have continued after the life of the project.

Data validation mechanisms developed by Genesys in CS7 are freely and openly accessible and the lessons learned in its construction are applicable to smaller systems. Since 2013, Genesys source code is publicly accessible and reusable under an open-source software license.

The Genesys project shows how beneficial it can be to deliver a system with which all collaborators and future users are comfortable, in terms of quality and usability. It demonstrates how collaborative programs and projects can strengthen the capacity of partners to undertake research on their own plant and fungal diversity, a sure way to secure value and longevity of partnerships.

4 | FUTURE PRIORITIES

For collections-based organizations the accelerated sharing of collections remains a central driver for collaborative work. The eight case studies presented in this article show how international collaborations deliver benefits that are impossible to achieve when work is carried out in isolation. Our review demonstrates how effective collaborations foster long-term relationships, instill a sense of trust and mutual respect between partners which encourages and promotes the sharing of data, material, technology, tools, and knowledge: prerequisites to halting biodiversity loss and rapidly unlocking the useful properties of plants and fungi for sustainable development.

Our case studies not only demonstrate many successes, but we also recognized three areas of collaborative collection sharing where significantly more progress needs to be made. **First**, there is an increasing need to improve access to collection information on plants and fungi. **Second,** there is a pressing need to improve the access to valuable living plant and fungal material. **Third**, once accessed, the exploration and use of plant and fungal material (herbarium samples, seed, living plant, or fungal material) must be accelerated, in a responsible and transparent way, particularly when modern rapid screening techniques are employed to discover plant and fungal properties.

4.1 | Improving access to collection information

The digitization of specimens from the world's largest herbarium and fungarium collections requires rapid completion (Borsch et al., 2020) and digital integration, such as that articulated by the Distributed System of Scientific Collections program (DISSCo, 2020). We must address the capacity of national and regional herbaria and fungaria to completely digitize their own collections and integrate their data into international platforms. Concurrently, the data quality of these digitized records (taxonomic accuracy, inclusion of geographic information) must improve to ensure their “fitness for use” (Gaijy et al., 2013). The IT infrastructure needed to aggregate and present these data to the global conservation community must also keep pace with the inevitable increase in specimen records.

The lack of provenance information on living collections held in botanic gardens essentially makes these collections largely opaque to users. While this has been addressed for certain groups of species (see Case Study 8) there needs to be a targeted and rapid upscaling of documenting accession provenance and exploring the underlying genetic diversity across collections of both living plants and fungi. This will allow, among other things, for an increase in their use for breeding programs supporting species conservation and contributing to the development of climate-resilient crops.

4.2 | Improving access to living material

We have already highlighted the value of increasing access to seed and other germplasm material held in genebanks (CS6 and CS7) and to living plant material of whole plants and seed from botanic gardens (CS8). Efforts to increase the exploration and use of fungi also has huge potential to support strategies against human and plant diseases, enhancing agricultural crops and forestry, food and beverages, waste disposal, and many facets of the bio-economies of Low to Middle Income Countries (LMICs; Hyde et al., 2019). While freeze drying techniques allow for the preservation of sporing fungi for up to 50 years (Smith & Onions, 1994), cryopreservation has become the standard technology for preservation of fungi in large culture collections and should, therefore, be further expanded (Ryan et al., 2019; Ryan & Smith, 2004). This technique is also successfully used for both ectomycorrhizal and arbuscular mycorrhizal fungi (Lalaymia, Cranenbrouck, & Declerck, 2014), organisms that will play an ever-increasing role in agriculture, food security, and medicine.

There is a need to establish in-country culture collections in LMICs, although they are expensive. In addition, access to these fungal resources under the CBD and Nagoya Protocol would need to be considered. Increasing the number of fungal collections available for use should, therefore, be dependent on the development of a smaller number of well-resourced collections. As with the development of any collection facility it is important that these are provided with core financial support rather than being dependent on the vagaries of short-term funding to individual research groups. This is an example of where collaborative science may well be best grounded in countries of high income, but with a complementary onus on these facilities strengthening international collaboration, joint research programs, and technology transfer.

Codes of conduct that promote transparency between providers and recipients of plant and fungal resources, such as those promoted in the EU regulations on ABS (European Commission, 2020), should be mainstreamed among collections-based organizations worldwide. Smart collections management systems need to track and make available the use, publications, and onward supply of any acquired material through the wide-scale application of digital object identifiers (DOIs) to individual collection accessions.

In stark contrast to the SMTA of the ITPGRFA, the more time-consuming use of bilaterally negotiated Material Transfer Agreements will benefit from the commitment to long-term collaborative programs between collections-based institutes. Such negotiated agreements need to provide accelerated and efficient access to collections from biodiverse areas of the world, and facilitate the rapid access to the advanced tools and technologies required to target and identify the many useful compounds and traits still waiting to be unlocked. Collaborations must hold firm on their adherence to the principles of the CBD and the Nagoya Protocol, protecting the rights of the guardians and custodians of that diversity and ensuring that any benefits that might accrue from its exploration and eventual use are appropriately shared.

4.3 | Accelerating responsible exploration of existing collections

The many thousands of plants and fungi used by humans are well documented (Allkin, 2017; McChesney, Venkataraman, & Henri, 2007; Ulian, Sacandé, Hudson, & Mattana, 2017). By increasing and accelerating our access to material held in global collections, the major challenges defined in the UN SDGs can be partially addressed by unlocking the many useful properties of plants and fungi (Antonelli et al., 2019). With the many tens of thousands of plant and fungal species represented in global collections yet to be explored, it is key to identify those groups of species that are most likely to contain the chemicals, properties, and traits that will prove to be useful. To this end, the establishment of phylogenetic relationships has proven a powerful toolkit (e.g., Gutaker et al., 2019; Rønsted et al., 2012). Exciting correlations between phylogeny and the production of certain useful chemical compounds are being uncovered. For example, a phylogeny of the Amaryllidoideae found strong relationships between alkaloid diversity and activity in bioassays related to the central nervous system (Rønsted et al., 2012). A recent study using historical herbarium material has traced the demographic and adaptive history of potato introduction and uncovered the likely evolutionary process of the adaptation of European potatoes to shorter day length and growing seasons (Gutaker et al., 2019). Further analysis of closely related species from existing collections and targeting of new collection priorities should follow.

It will also be important to put increased focus on population level phylogenetic sampling, since there is likely to be large intra-specific variation in relation to environmental adaptations, defense mechanisms, and other factors that may lead to different phenotypic expression (Maldonado et al., 2017). The availability and maintenance of appropriate analytical equipment for identifying useful plant compounds is largely confined to the wealthier collections-based research institutes, which will be far more readily available as a result of strong international collaboration.

In conclusion, we have highlighted the need to build and protect the trust and mutual respect within and between collaborative teams and to ensure that the use of biological collections is undertaken responsibly and with transparency. Maintaining these fundamental principles of collaboration will undoubtedly ensure sustainable management and use of our plant and fungal resources and address the challenges articulated in the SDGs.

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